AAS 17-157

IN-FLIGHT POINTING ACCURACY ASSESSMENT AND GNC COMMISSIONING OVERVIEW FOR THE DUAL-SPINNING SMAP (SOIL MOISTURE ACTIVE PASSIVE) SPACECRAFT

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NASA's new SMAP (Soil Moisture Active Passive) spacecraft is a radar and radiometer-based climate monitoring mission that, for an earth-orbiting satellite, presented an uncommonly large engineering challenge for the spacecraft designers at NASA's Jet Propulsion Laboratory. The primary engineering challenge of this mission was to design a three-axis stabilized dual-spinning spacecraft with the largest spinning flexible mesh reflector of any known spacecraft. This paper reports on the attitude control performance of this duel-spinning conical-scanning system during the first 18 months of science operations, and provides an overview of the Guidance, Navigation, and Control (GNC) subsystem performance for this climate monitoring asset.

SMAP MISSION OVERVIEW

The 944 kg Soil Moisture Active Passive (SMAP) spacecraft is in a 685 km polar sun-synchronous low earth orbit. Its mission is to produce high-accuracy global measurements of soil moisture levels in the top two inches of soil with 9 km resolution and map the global freeze/thaw boundary at 3 km resolution, and to repeat those measurements no less frequently than every 2-3 days.[1,2] The National Research Council's 2007 Decadal Survey of Earth science missions identified soil moisture measurements as a top priority due to the value of the soil moisture data for drought and flood monitoring and mitigation, as well as global climate modeling. To accomplish the science mission, the SMAP spacecraft is outfitted with two science instruments: an L-Band Radiometer operating at 1.41 GHz, and a tunable L-Band Radar operating from 1.22-1.3 GHz.[2] Ground post-processing of the combined data from the two instruments allows for the creation of a unified science data product which benefits from the high spatial resolution of the Radar instrument and the high accuracy soil moisture measurements of the Radiometer instrument. However, in July 2015, just two months into the science mission, the Radar instrument suffered a hardware component fault which permanently disabled the transmit capability of the Radar and rendered the instrument inoperable.[3] The failure of the Radar instrument was a significant blow to the overall quality of the soil moisture data; dropping the resolution of both the soil moisture and freeze/thaw boundary measurements to ~25 km resolution. Nevertheless, the SMAP science mis-

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sion continues with the spacecraft producing global soil moisture maps from the remaining Radiometer instrument data.[3]

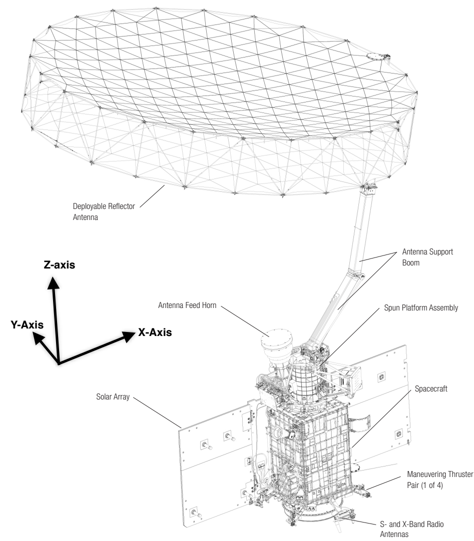

Figure 1. NASA's Soil Moisture Active Passive (SMAP) spacecraft. The anti-sun facing side of the spacecraft is visible here, with the solar arrays, boom and mesh reflector in the fully deployed science configuration.

The SMAP spacecraft mechanical design is shown in Figure 1 and consists of a spun and de-spun portion of the spacecraft. The primary spacecraft bus, with solar array wings and all GNC attitude control hardware, is on the de-spun portion of the spacecraft, which maintains a fixed attitude that aligns the –Z spacecraft axis with the geodetic nadir direction.[4] The upper portion of the spacecraft is known as the Spun Platform Assembly (SPA) and consists of a 6-meter diameter deployable parabolic mesh reflector affixed to a 5-meter long rigid boom.[5] The boom and reflector are collectively known as the Reflector Boom Assembly (RBA). In addition to the RBA, the SPA also includes the radiometer feed-horn and various radar and radiometer hardware. During science operations, the SPA maintains a constant 14.6 rpm spin-rate.[6,7] The spinning reflector allows the narrow beams of the radar and radiometer instruments to be conically scanned across all azimuths at a constant angle elevated 35.5 degrees relative to the nadir direction.[6] The conical scanning motion of the SPA is required in order for the science instruments to achieve global coverage within 3 days.

GNC SUBSYSTEM OVERVIEW

A detailed description of the GNC subsystem hardware checkout and commissioning activities was previously reported[7], so the primary purpose of this paper is to report on the achieved pointing accuracy following nearly 2 years of science operations. As background, some basic information about the GNC subsystem is required. The GNC attitude estimator combines data from a stellar reference unit (SRU), sampling inertial attitude at 8 Hz, with data from one of two redundant inertial reference units (IRUs) measuring spacecraft body rates at 200 Hz. Although normally the data from both the IRU and SRU are used in the control loop, the spacecraft does experience regular SRU obstructions, during which IRU-only (gyro-only) attitude propagation is required. The SMAP Flight System was designed to meet full science pointing accuracy requirements with SRU outages up to 17 minutes.

The GNC hardware on SMAP also includes two cosine-type coarse sun sensor pyramid assemblies (CSS) which are used for attitude initialization following spacecraft safing events. Though the sun sensor data is used by the attitude estimator during safe mode operation, during science operations the sun sensors are used only as a sanity check against the inertial attitude estimate and onboard ephemeris.

Even with the large boom and reflector on the SPA spinning at 14.6 rpm, SMAP is a 3-axis stabilized dual-spinning spacecraft. Attitude control on SMAP can be achieved with either a set of eight 4.5 N reaction control system (RCS) thrusters, or via a set of four 250 Nms reaction wheel assemblies (RWAs). During science operations, the angular momentum of the SPA spinning at 14.6 rpm is precisely countered by the four large RWAs, such that the spacecraft actively maintains a targeted zero-momentum state. In flight, the estimated spacecraft angular momentum magnitude never grows above 0.3 Nms during nadir-pointed science operations.[7]

To maintain the zero-momentum state, the GNC hardware includes a three-axis magnetometer (TAM) as well as a set of 3 orthogonal magnetic torque rods (MTRs) aligned with the spacecraft body axes. Whenever the spacecraft is under RWA control, a momentum control loop remains active and runs in parallel to the attitude control loop. An onboard momentum estimator uses spacecraft body rate data, along with spin-rate estimates for the SPA and RWAs to produce an estimate of the current spacecraft angular momentum. Data from the TAM provides the direction of the external magnetic field of the Earth so that the momentum controller can determine the correct duration and voltage polarity to be applied to each MTR to reduce the magnitude of the estimates momentum vector.

To counter the large 359 Nms angular momentum of the spinning SPA, the four SMAP reaction wheels are mounted with their spin-axes skewed toward the spacecraft Z-axis to provide significantly more momentum storage capacity in that direction. In total, the SMAP RWAs provide a usable momentum capacity in excess of 384 Nms for the Z-axis and between 50-120 Nms for X and Y axes momentum control depending on whether the SPA is spinning. Since the SPA has spun continuously since the initial spin-up in March 2015, the RWAs have remained at spin-rates between 2200-2700 rpm. Between launch and the writing of this paper in December 2016 the RWAs have accumulated between 2.0-2.3 billion revolutions each. In addition to countering the angular momentum of the SPA, it is the reaction wheel controller that is also responsible for meeting the science pointing requirements.

WOBBLE OF THE SPUN PLATFORM ASSEMBLY

The greatest GNC challenge for the SMAP mission was to design a system and that would allow for accurate science pointing in the presence of the imbalances of the large spinning RBA.[6] While many spacecraft, especially those in geostationary orbits, have deployable mesh reflectors significantly larger than SMAP's, SMAP is believed to be unique among Earth-orbiting spacecraft in maintaining 3-axis control with a spun-platform so large that it dwarfs the size of the spacecraft it is affixed to.[6] In fact, the moment of inertia of the SPA is effectively identical to the inertia of the de-spun portion of the spacecraft. The I_{zz} moment of inertia of the SPA (the Z-axis is the spin-axis) was measured in flight to be 234.71 kg-m^2, while the I_{zz} moment of inertia of the de-spun portion of the spacecraft was calibrated to be 235.7 kg-m^2. Due to the large size of the SPA, the RWA attitude controller is consequently very sensitive to any spun-imbalances of the rotating SPA.

Any non-zero products of inertia (POIs) for the spinning SPA result in a wobble that manifests as small oscillatory body rates in the X and Y axes that cause the spacecraft Z-axis to follow an elliptical (nearly circular) path around the ideal nadir pointing vector (an example of this wobble ellipse is shown later in Figure 4). Early in the spacecraft design process, the project elected to forego the mass and complexity associated with using actuated balance masses to perform in-flight system balancing. Instead, the SMAP project adopted a strategy where: (1) a limit on the maximum permissible wobble-induced nadir bias was defined by the SMAP Dynamics and Control team, (2) this nadir bias angle limit was mapped into a limit on the effective product of inertia (EPOI) of the SPA around its spin-axis, and (3) the mechanical team designed the spacecraft with tolerances that guaranteed that the limit on the EPOI would not be exceeded.[6] Note that this strategy guaranteed that any non-zero wobble would persist for the entire mission and that the RWA controller must therefore function in the presence of the wobble.

The bandwidth of the SMAP RWA attitude control system (ACS) is 0.03 Hz whereas the antenna science spin-rate (14.6 rpm) induces a wobble with a frequency of 0.243 Hz.[7] Since the wobble frequency is outside the RWA controller bandwidth, the RWA controller cannot be used to control the wobble. Instead, the GNC team implemented a controller design that utilizes a double notch filter, where the first notch is tuned to the 0.243 Hz wobble frequency and the second notch is tuned to the first harmonic. In this way, the RWA controller is designed to maintain attitude control without attempting to "fight" the natural wobble motion that is inherent to the mechanical system design. The unfiltered attitude control error for the X & Y axes shows a strong oscillatory signature at the 0.243 Hz frequency and the *filtered* attitude control error removes all apparent traces of the wobble oscillation.

The RWA controller design guarantees that the average position of the Z-axis is accurately aligned with the commanded nadir direction, even though the instantaneous Z-axis pointing direction is tracing circles around that direction. The double notch filter design in the RWA controller is only effective at the science spin rate (14.6 rpm), so during the controlled spin-up from 5 rpm to 14.6 rpm the wobble introduces disturbances that fall outside the notches and the RWA controller performance is significantly worse.[7] However, this is acceptable because the science pointing requirements are only enforced at the science spin-rates and the coarser attitude control performance at other spin-rates still provides the robustness needed for spacecraft safety.

An earlier publication[7] provides additional detail on the SMAP GNC hardware, commissioning activities, and GNC controller functionality. However, that publication[7] (shortly after the completion of commissioning) came too soon to report on the long-term pointing accuracy and stability of the SMAP spacecraft. This paper provides verification that the GNC subsystem is meeting the pointing accuracy requirements.

SMAP GNC POINTING ACCURACY REQUIREMENTS

The pointing architecture used by the SMAP project was described in extensive detail in a prior publication.[6] To summarize, the project developed six Flight System (which includes both the "Spacecraft" and the "Instrument") level pointing accuracy, stability, and knowledge requirements that were used to constrain the system design and ensure that the science goals of the mission would be met.[6] Several of the Flight System pointing requirements will be covered in much more detail later in the paper. For each of the six pointing requirements, a detailed pointing budget was developed, in which small allocations of pointing error were apportioned to every possible error source the engineers on the project expected the Flight System to encounter.[6] In these pointing budgets, the GNC subsystem receives a pointing accuracy allocations. The Flight System allocation to GNC was then re-expressed as GNC *subsystem* pointing accuracy requirements that the GNC team could evaluate with detailed dynamic and kinematic simulations. Table 1 provides a summary of the four key GNC subsystem pointing requirements. These requirements drove the hardware performance requirements of various GNC hardware (including the IRU, RWA, and MTR), and also drove the design of the GNC attitude control algorithms and operation modes. In Table 1 a summary of the requirement text is provided, and you can see that the structure of these requirements was to specify a "shall not exceed" value as a 3-sigma bound for a rolling one-month window of science operations. Said another way, during the science mission, at any instant the performance of the GNC subsystem over the previous 30 days must comply with these accuracy requirements.

Table 1. SMAP Key GNC Subsystem Pointing Accuracy Requirements versus In-Flight Performance

GNC Pointing Requirements	GNC Requirement Summary	Unit	Requirement	Pre-Launch Expectation	Flight Telemetry	Achieved Margin	Comply?
GNC Absolute Pointing Error (X & Y Axes)	Over a one-month period of science ops, GNC must maintain the absolute pointing error angle about the SC X & Y axes (excluding wobble) to within 0.1 deg (3σ)	deg	0.1	0.06	**0.002**	**98%**	Yes
GNC Absolute Pointing Error (Z-Axis)	Over a one-month period of science ops, GNC must maintain the absolute pointing error angle about the SC Z axis (excluding wobble) to within 0.28 deg (3σ)	deg	0.28	0.12	**0.066**	**76%**	Yes
GNC Angular Rate Error	Over a one-month period of science ops, GNC must maintain the angular rate of the spacecraft (excluding wobble) to less than 0.070 deg/s (3σ)	deg/sec	0.07	0.04	**0.022**	**69%**	Yes
GNC Attitude Knowledge Error	Over a one-month period of science ops, GNC must ensure that the estimated attitude knowledge error is less than 0.04 deg (3σ)	deg	0.04	0.02	**0.001**	**97%**	Yes

For the GNC pointing accuracy requirements in Table 1, note that there is a tighter pointing accuracy requirement on the X and Y axes (0.1 degrees) than there is on the Z-axis (0.28 degrees) because the Z-axis, apart from being the minimum moment of inertia, is also subject to disturbances from the SPA spin-motor; which is known as the BAPTA (bearing and power transfer assembly).[7] In fact, the dominant Z-axis attitude disturbance source is a 70 second period ~22 milli-degree oscillation caused by the BAPTA bearing harmonic.

The absolute pointing error performance of the RWA attitude controller relative to the requirement limits (Figure 2) can be observed by comparing the per-axis filtered attitude error over a recent representative one-month period of science operations to the error limit specified in Table 1. The one-month period of science collection shown in Figure 2 spanned from November 12 through December 12 of 2016 and actually constituted the longest period of uninterrupted science over the course of the mission to date. Prior to these 31 days, previous periods of science collection had been interrupted by orbit trim maneuvers, Flight Software maintenance activities, spacecraft anomalies, and off-nadir instrument calibration activities (i.e. spacecraft slews). During this 31-day science period, the spacecraft remained at the nadir pointing science attitude with the SPA maintaining a constant 14.6 rpm spin-rate, and with the Radiometer science instrument collecting the namesake soil moisture data.

A close examination of the Y-axis filtered attitude error telemetry in Figure 2 shows one large spike of approximately 6 milli-degrees near the end of the month. This spike was caused by a multi-week interruption to the ground system that computes the correlation between spacecraft clock (SCLK) time and ephemeris time. The ground process interruption ultimately resulted in a minor ephemeris discontinuity due to the un-modeled timing drift of the SCLK. This spike is an excellent example of the type of unplanned idiosyncrasies which typify real-world spacecraft operations. The GNC team chose to leave this outlier event in the data because it serves as an example of why the GNC pointing requirement in Table 1 are specified as 3-sigma bounds. The Y-axis spike in Figure 2 is a 7-sigma outlier in the data; something that should statistically never happen due to Gaussian fluctuations in the data (probability of 3 parts per trillion), but which nevertheless *does* happen due to the non-Gaussian complexity of the flight vehicle and ground system.

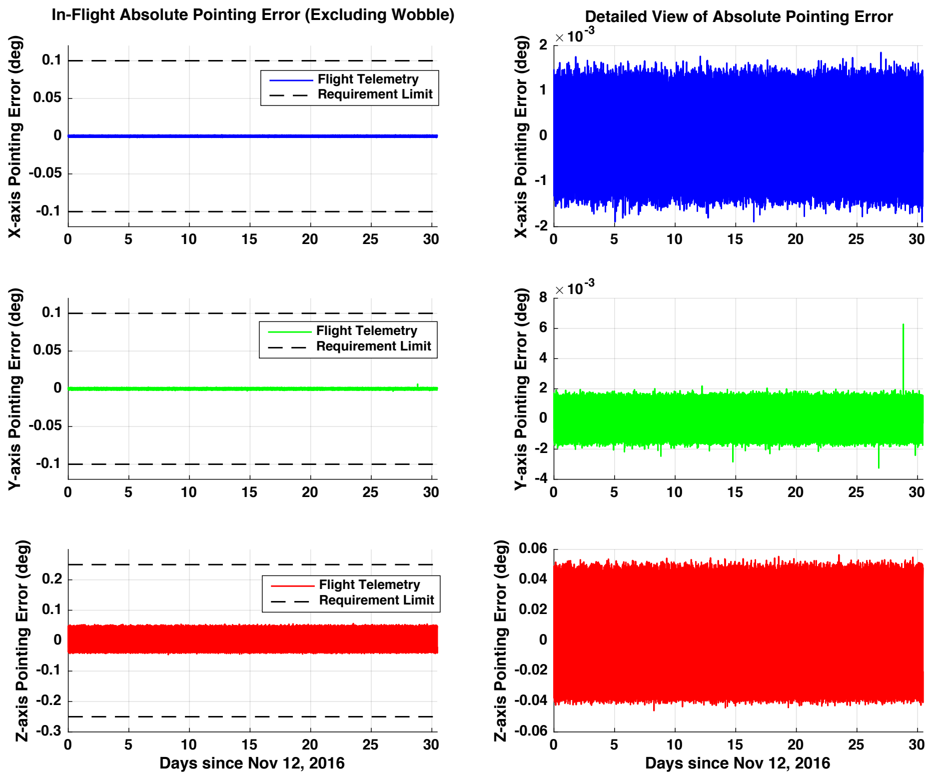

Figure 2. SMAP GNC absolute pointing error for a representative one-month period of uninterrupted science operations. The left-hand plots compare the attitude error to the requirement bounds (dashed lines). The right-hand plots show narrower range for additional detail. The GNC pointing error shown here (i.e. the filtered attitude control error) does not include the wobble motion that exists in the X & Y axes.

In flight, the GNC subsystem has demonstrated excellent performance in meeting the pointing accuracy requirements (the first two requirements in Table 1). The magnitude of the filtered attitude control error never even approaches the requirement limits denoted with dashed lines in Figure 2. Since the GNC pointing accuracy requirements in Table 1 are specified as 3-sigma bounds, a Normal Distribution was fit to the 1.5 million telemetry data points available for each axis to find the achieved mu and sigma terms. The computed 3-sigma value for each of the body axes is shown in Table 1 in green and can be compared to both the requirement limit as well as the pre-launch GNC expectation of the pointing performance. The GNC subsystem meets the absolute pointing accuracy requirements with 98% margin for the X & Y axes and 76% margin for the Z-axis.

The third GNC requirement in Table 1 limits the absolute spacecraft body rate error to less than 0.070 deg/s (3-sigma) over one month of science operations. The spacecraft body rate over the same one-month period is shown in Figure 3. The telemetry for each body-axis clearly falls well within the 3-sigma requirement limits (dashed lines). Again, a Normal Distribution was fit to the data in Figure 3 and the 3-sigma values for the three axes were found to be 22 milli-deg/s for the worst axis (the Z-axis), which was significantly less than the 40 milli-deg/s expected by the GNC team pre-launch, and maintains 69% margin below the 70 milli-deg requirement shown in Table 1.

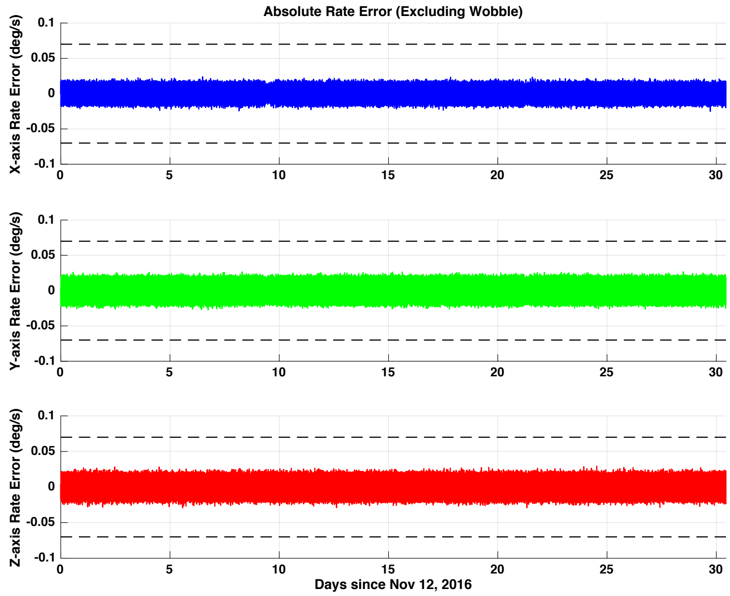

Figure 3. SMAP spacecraft absolute rate error telemetry measured over one month of science data collection. During this period the spacecraft remained continuously at the nadir pointed attitude with the SPA spinning at 14.6 rpm.

The fourth and final GNC pointing accuracy requirement from Table 1 limits the GNC attitude knowledge error over one-month of science operations to better than 0.04 degrees (3-sigma). Attitude knowledge refers to how accurately the SRU-based attitude is known relative to the inertial J2000 reference frame. During normal operations, the GNC attitude knowledge error is largest during periods where the SRU is obstructed by a bright body (i.e. Sun, Moon, or Earth) and the attitude estimate is derived from the integrated IRU body rate data. Therefore, in-flight attitude knowledge error can be quantified by determining (1) the achieved IRU-only attitude propagation error drift-rate and (2) the maximum amount of time that IRU-only attitude propagation is required during any one month of science operations.

Although the SRU is never obstructed by the Earth or Sun while at the science attitude, moon occultations do occur regularly. Due to SMAP's polar orbit, every two weeks the Moon passes through the wide planar swath swept out by the SRU field of view and results in SRU obstructions lasting up to 5.5 minutes. Although the SRU rarely loses lock on star patterns even when the Moon is in the SRU field of view, the attitude estimator nevertheless ignores the SRU data when the moon is near the center of the SRU images to avoid using attitude estimates with large error. No SRU outage of longer than 5.5 minutes has occurred during normal science operations.

The second requisite piece of information for quantifying attitude knowledge error is the attitude error accumulated due to IRU-only attitude propagation. The IRU propagation error in this case is the sum of the rate bias, scale factor error, IRU to SRU alignment knowledge error. The IRU-to-SRU alignment was calibrated during the spacecraft commissioning[7], so it should be minor except for thermomechanical variations. Therefore, the majority of the IRU propagation error should come from rate bias and scale factor error, with the latter expected to be the dominant term.

When the spacecraft enters Safe Mode, the GNC flight software transitions to an IRU-only attitude propagation mode and maintains a slow rotisserie roll around the spacecraft Y-axis; attempting to keep the Y-axis pointed in the pseudo-inertial direction where the Sun was sensed by the Coarse Sun Sensors. The operations team has the ability during safe mode to power on the SRU and receive inertial attitude measurements even though the GNC flight software does not use the SRU data in the control loop. In this way, it is possible to observe IRU propagation error during Safe Mode operations, provided that the SRU has been powered on by the operations team, and sufficient time is allowed for the attitude uncertainty to accumulate to measurable levels. However, since there is a strong desire from the project to limit the duration of science interruption due to safing events, long duration opportunities to observe gyro-only attitude propagation rarely occur.

Table 2 provides the date and duration of all six in-flight occurrences where the spacecraft propagated attitude knowledge using only the IRU, while the SRU was observing for periods longer than 1 hour. The angular error reported in Table 2 is measured between the commanded inertial body axis pointing and the actual attitude measured by the SRU. Larger attitude drift seen for the X and Z axes (Table 2) is a result of the slow Y-axis rotisserie roll that the spacecraft performs during Safe Mode operations. Since the commanded spacecraft attitude is rolling about the Y-axis, the commanded pointing direction of the X-axis and Z-axis are rotating relative to the inertial frame while the Y-axis maintains an inertially fixed pointing direction. The larger error in X and Z compared to Y implies that the dominant error source for gyro propagation is the scale factor error.

Table 2. SMAP in-flight IRU propagation error during periods of extended IRU-only attitude estimation. Gyro-only propagation error is measured by comparing the measured spacecraft attitude propagating on IRU against the expected (i.e. commanded) spacecraft attitude. The bottom two entries should be given less weight due to their short durations.

Date	Duration of Attitude Propagation Using Only IRU Data (Hours)	Per-Axis IRU Attitude Propagation Uncertainty (deg/day)**		
		X-Axis	Y-Axis	Z-Axis
2/7/2015	49.6	0.30	0.03	0.30
2/19/2015	18.7	0.29	0.03	0.29
5/12/2015	24.9	0.24	-0.05	0.22
6/16/2015	22.4	0.18	0.01	0.20
9/5/2016	1.6	0.23	0.01	0.12
9/27/2016	2.3	0.14	0.45	0.22

**Measured as the angle between the commanded J2000 pointing of each of the spacecraft body-axes and the actual pointing of the spacecraft body-axes measured with SRU telemetry

The first significant period of IRU propagation that occurred, and where SRU data was also collected, occurred one week after launch on 2/7/2015. At that time the operations team chose to leave the spacecraft in Safe Mode for >2 days in order to investigate an SRU anomaly.[7] The IRU-propagation error growth rate is seen to be 0.63 deg in X and Z across 49.6 hours. Although the latter entries in Table 2 show slightly lower error growth rates, there was significantly less SRU data collected during these events, and the last two events in Table 2 should be given very little weight because the IRU propagation only lasted for 1-2 hours. For the purpose of quantifying the attitude knowledge error, the realistic IRU propagation error growth rate can be bounded by 0.3 deg/day.

Having quantified the worst-case SRU data outage experienced during science operations (5.5 minutes) as well as the in-flight IRU propagation error rate (0.3 deg/day), the worst-case GNC attitude knowledge error at the end of a 5.5 minute SRU Moon occultation is estimated to be 1.1 milli-deg. This superb performance preserves 97% margin against the GNC attitude knowledge requirement shown in Table 1.

At this juncture, we have shown that the SMAP GNC subsystem meets all four of the GNC pointing accuracy requirements with substantial margin. Not only does the GNC subsystem comply with the requirements, it also substantially outperforms the pre-launch expectations of the subsystem. The GNC subsystem provides a consistent and stable platform for science observations that meets all pointing accuracy requirements. The next section will discuss the pointing accuracy of the full Flight System, rather than considering only the GNC subsystem.

SMAP FLIGHT SYSTEM POINTING ACCURACY REQUIREMENTS

As previously described, the SMAP project maintained pointing budgets for Flight System leveling pointing requirements, and the GNC pointing performance was only one of many factors included in the pointing budgets.[6] As a reminder, “Flight System” refers to the full integrated “Spacecraft” and “Instrument” and encompasses all flying components of the spacecraft. The Flight System nadir pointing accuracy requirements are shown in Table 3. These three nadir accuracy requirements constitute three of the six Flight System pointing requirements, with the other three limiting the azimuthal pointing error of the SPA.[6] This paper will not provide any discussion of the azimuthal pointing error because the dominant sources of azimuthal error are due to timing and position uncertainties of the SPA; these factors cannot be analyzed using only the GNC flight telemetry.

The limits on the 3-sigma nadir pointing accuracy, stability, and knowledge are shown in Table 3. While the GNC team can report here on the attitude control contribution to the Flight System nadir pointing, it is impossible for the GNC operations team to verify the *full* Flight System pointing performance. There are many causes of pointing error for the SMAP Flight System including: biases in the electro-mechanical boresight of the science instrument or attitude sensors, thermomechanical distortions in either the spacecraft or science instruments, antenna flex and deformation due to centripetal acceleration, spacecraft wobble due to the imbalance of the spinning RBA, attitude error due to limitations of the GNC controller or attitude estimator, torque irregularities from the BAPTA spin motor, RF scattering of the radar or radiometer data, and even disturbances from the static and dynamic imbalances of the fast spinning RWAs. The Spacecraft (which includes the GNC subsystem) received a pointing accuracy allocation, shown in red in Table 3, that was a fraction of the overall Flight System pointing requirements shown in blue.

Table 3. SMAP Key Flight System Nadir Pointing Accuracy Requirements

Flight System Pointing Requirements	Flight System Requirement Summary	Unit	Requirement (Spacecraft + Instrument)	Spacecraft Allocation	Pre-Launch Expectation	Flight Telemetry	Margin Relative to Spacecraft Allocation	Comply?
System Nadir Bias Angle	Over a one-month period of science ops, the observatory mean boresight nadir angle (including wobble) must be biased no more than 0.5 deg (3σ) from the commanded nadir pointing direction	deg	0.5	0.2	0.072	**0.033***	**84%**	Yes
System Nadir Stability	Over a one-month period of science ops, the instantaneous observatory boresight nadir angle (including wobble) must remain within 0.3 deg (3σ) of the mean antenna boresight nadir angle	deg	0.3	0.14	0.073	**0.003***	**98%**	Yes
System Nadir Knowledge	During Science observations, the antenna boresight nadir angle must be **known** to within 0.1 deg (3σ) of instantaneous antenna boresight nadir angle	deg	0.1	0.07	0.045	**0.004***	**94%**	Yes

*Note: Only the GNC *measurable* components of the error are reported. Thermo-mechanical variations of the hardware, command system idiosyncrasies, RF scattering, and instrument induced error sources are not considered because they cannot be quantified from available telemetry

As shown in Table 3, the nadir pointing accuracy requirements for the Flight System limit the 3-sigma mean nadir bias, nadir pointing stability, and nadir knowledge for one month of science operations. As a definition, the nadir bias is the angle between the instantaneous antenna pointing angle achieved in flight and the planned (or commanded) nadir pointing angle. Although the spacecraft was designed so that the SPA spin-axis would be exactly aligned with the spacecraft Z-axis, there is a non-zero mechanical misalignment in the true flight system and this misalignment results in a nadir bias. More significantly, the center of mass of the SPA is slightly offset from the SPA spin-axis, and as a result the spacecraft experiences the previously described wobble motion (Figure 4). The offset between the spun center of mass and the SPA spin-axis results in an effective product of inertia (EPOI). For SMAP the EPOI of the SPA could be no larger than 4 kg-m^2 at the science spin-rate[6], and the system level limit on the observatory's mean boresight nadir angle could be biased no more than 0.5 degrees (3-sigma) from the nominal nadir direction over a period of one month of science operations.

The wobble induced nadir bias of the SMAP Flight System is shown graphically in Figure 4, where on the left, the *unfiltered* X and Y attitude control errors are plotted against one another. The unfiltered attitude control errors trace out an elliptical (though very nearly circular) trajectory that is offset from the desired nadir pointing direction by 33 milli-degrees (3-sigma). The center plot of Figure 4 shows the time history of the nadir bias angle that is computed as the RSS of the X and Y attitude error from the left-hand plot. The nadir bias magnitude in the center plot of Figure 4 is effectively a measure of the spacecraft wobble angle, and is compared to the Flight System absolute nadir accuracy requirement, 0.5 degrees, and to the 0.2 degree GNC/Spacecraft allocation. The observed in-flight wobble is far smaller than the requirement limits. In fact, the wobble induced nadir offset maintains 84% margin below the GNC allocated limit. However, this comparison provides an incomplete understanding of the system pointing performance, because the wobble amplitude visible in the GNC telemetry is only a single contributor to the full Flight System nadir bias, and most of the budgeted sources of pointing error are not reflected in the GNC telemetry. For example, knowledge error in the orientation of the SRU relative to the body frame would manifest itself as a nadir pointing error, even if the attitude controller performance was flawless. Although the orientation of the SPA spin-axis relative to the SRU was calibrated shortly after the spin-up to 14.6 rpm, it is unknown whether this orientation varies with time or due to temperature changes.

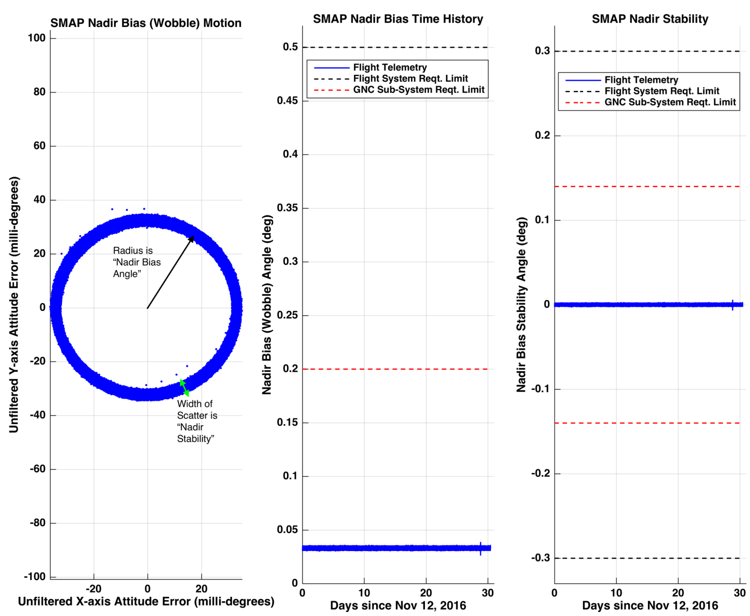

Figure 4. SMAP Nadir Bias motion and time history, and Nadir Stability shown for a one-month period of science data collection.

The left-hand plot in Figure 4 assumes that the origin in X and Y is equivalent to the SPA spin-axis being pointed *exactly* in the true geodetic nadir direction, though it is possible that SPA spin-axis knowledge error could result in the entire circular wobble trace in Figure 4 being offset from the true nadir direction. To counteract any fixed nadir bias, early in the mission the nadir bias offset was computed by analyzing the return time of Radar transmitted pulses across many SPA revolutions. This information was used to update the flight software knowledge of the SPA spin-axis. The SPA spin-axis was found to be offset from the planned mechanical orientation by 72 milli-deg in X and 21 milli-deg in Y. The results of the calibration were used to update the commanded Z-axis pointing direction to achieve true nadir pointing. However, since the Radar instrument on the spacecraft failed in July 2015[7,3] it is not possible to repeat this calibration, and thus it is not possible to determine whether the nadir bias offset has shifted over time. No alternative method of calibrating the nadir bias offset is available, and therefore the value computed prior to the Radar failure is the best estimate, and will be used for the remainder of the mission.

The second Flight System requirement in Table 3 places a limit on the nadir stability. The nadir stability is defined as the angle between the instantaneous antenna pointing angle and the one-month *mean* antenna bias angle. In effect, this is a measure of how much scatter and variability there is in the nadir bias. The GNC-achieved nadir stability is shown in the right-hand plot of Figure 4 and was computed as the difference between the instantaneous nadir bias angle (center plot) and the one month mean nadir bias value. The 3-sigma variation in the GNC measured nadir stability is only 3 milli-deg, which is far smaller than the GNC allocation of 140 milli-deg and the Flight System limit of 300 milli-deg. Based on GNC telemetry, the attitude controller maintains 98% margin (3-sigma) below the nadir stability allocation. Once again, it must be emphasized that the nadir stability shown in Figure 4 only reflects the portion of the nadir stability which is measureable from GNC telemetry. Time-varying thermomechanical variations in the spacecraft structure, as well as RF scattering, and other significant error sources cannot be observed in GNC telemetry, and many cannot be quantified in-flight. Nevertheless, the GNC attitude controller again demonstrates excellence performance that exceeds the conservative GNC pre-launch expectations.

The final Flight System pointing accuracy requirement in Table 3 limits the Flight System nadir knowledge to better than 0.1 degrees (3-sigma). The nadir knowledge can be computed as the sum of three contributors: first, the variation in the nadir bias over one month relative to the one month mean value. Second, a linear drift term that is a function of the worst-case time that the Flight System is without data from the SRU, and third, the 3-sigma nadir bias stability range. The latter two pieces were previously computed. As for the variation in the nadir bias over one month, this term, while smaller than the gyro propagation error seen during SRU outages, is still measurable from GNC telemetry.

As discussed in a previous publication[7], the magnitude of the wobble angle has shown a nearly linear growth over the course of the mission. Shortly after the SPA was initially spun-up to the science spin-rate the wobble magnitude had a daily average of 29.8 milli-deg, but that wobble magnitude has grown to 33.0 milli-deg as of December 2016. Nobody on the SMAP team definitively knows the source of the wobble amplitude change, but several lines of evidence suggest that the inertia properties of the RBA (which includes the boom and reflector) are slowly changing due to thermomechanical variations or relaxation in the presence of the centripetal acceleration. Regardless of its source, the wobble angle is growing at a rate of approximately 0.16 milli-deg/month.

Returning then to the topic of computing the Flight System nadir knowledge, the sum of the nadir bias variation, attitude drift due to SRU outages, and nadir stability results in a computed Flight System nadir knowledge of 4 milli-deg (Table 3), which preserves 94% margin relative to the 0.07 degree nadir knowledge allocation provided to the Spacecraft. As with the other two Flight System pointing requirements, it must be emphasized that this Flight System nadir knowledge computed here captures only the portions of the nadir knowledge that are visible in

GNC telemetry. Other significant error sources are not included here because they either cannot be quantified in flight, or are not visible with the information available to the GNC team.

CONCLUSION

The SMAP spacecraft is unique among known spacecraft for having such a large fraction of the spacecraft mass and inertia spinning at a high rate while also maintaining precise three-axis attitude control. The former SMAP project manager joked that SMAP was an example of "the tail wagging the dog," and this is an apt analogy. Even though the inertia of the SPA, which is spinning at 14.6 rpm, is nearly identical to the inertia of the de-spun portion of the spacecraft, the GNC subsystem is still required to meet several pointing accuracy requirements. We have shown here that the GNC subsystem pointing accuracy over the course of nearly two years of science operations has significantly outperformed all GNC pointing accuracy requirements. All four GNC pointing accuracy requirements were met with at least 69-98% margin.

Furthermore, the Flight System nadir accuracy requirements were compared to the in-flight nadir accuracy, stability, and knowledge estimated from GNC telemetry. As emphasized multiple times, this comparison should be treated cautiously because not all significant sources of nadir pointing error can be observed with GNC telemetry. That said, from what is visible in GNC telemetry, the SMAP Flight System clearly has a wobble induced nadir bias which is substantially smaller than the Flight System was designed to accommodate (0.033 degrees vs 0.5 degrees). The GNC telemetry indicates that all of the Flight System nadir accuracy requirements are met with margin of 84-98% relative to just the portion of the nadir accuracy that was allocated to the Spacecraft. Although not every source of error could be included in this accounting, there is every indication from the quality of the soil moisture data that is being returned daily and included in weather forecasts and climate models that the pointing performance exceeds expectations. Therefore, SMAP's *engineering challenge* to design and build a stable nadir pointed system that includes a large spinning mesh reflector has been an unqualified success.

ACKNOWLEDGMENTS

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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